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Head impact velocities in FIS World Cup snowboarders and freestyle skiers: Do real-life impacts exceed helmet testing standards?

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ABSTRACT

Introduction Prior to the 2013–2014 season, the International Ski Federation (FIS) increased the helmet testing speed from a minimum requirement of 5.4 to 6.8 m/s for alpine downhill, super-G and giant slalom and for freestyle ski cross, but not for the other freestyle disciplines or snowboarding. Whether this increased testing speed reflects impact velocities in real head injury situations on snow is unclear. We therefore investigated the injury mechanisms and gross head impact biomechanics in four real head injury situations among World Cup (WC) snowboard and freestyle athletes and compared these with helmet homologation laboratory test requirements. The helmets in the four cases complied with at least European Standards (EN) 1077 (Class B) or American Society for Testing and Materials (ASTM) F2040.

Methods We analysed four head injury videos from the FIS Injury Surveillance System throughout eight WC seasons (2006–2014) in detail. We used motion analysis software to digitize the helmet's trajectory and estimated the head's kinematics in two dimensions, including directly preimpact and postimpact.

Results All four impacts were to the occiput. In the four cases, the normal-to-slope preimpact velocity ranged from 7.0(±SD 0.2) m/s to 10.5±0.5 m/s and the normal-to-slope velocity change ranged from 8.4±0.6 m/s to 11.7±0.7 m/s. The sagittal plane helmet angular velocity estimates indicated a large change in angular velocity (25.0±2.9 rad/s to 49.1±0.3 rad/s).

Conclusion The estimated normal-to-slope preimpact velocity was higher than the current strictest helmet testing rule of 6.8 m/s in all four cases.

INTRODUCTION

According to the SnowSport Industries America, in the 2014–2015 season, there were approximately 7.7 million snowboarders (62% male, 38% female) and 4.5 million (59% male, 41% female) freeskiers in the USA alone.[1] However, recent studies have documented that injury rates in snowboarding and freestyle skiing are high, both at the competitive and recreational level.[2–6]

At the International Ski Federation (FIS) World Cup (WC) level, head injuries account for 12% of injuries that require medical attention in freestyle, alpine and snowboarding athletes.[7] Of these, 82% are concussions of which 24% are severe, leading to an absence from training or competition for more than 28 days.[7] However, this severity rating is an operational injury definition typically used for injury surveillance in sports, and not a head injury-specific severity rating.

Traumatic brain injuries (TBIs) are the leading cause of death in recreational skiers and snowboarders and are linked to acrobatic and high-speed activities.[5 8] In terrain parks, the majority of injuries occur on jumps and aerial features that promote a large drop to the ground.[9 10] Snowboarders are significantly more likely to sustain head/neck or trunk injuries than upper extremity injuries on aerial features, and the most commonly injured anatomic location for skiers using aerial features in a terrain park is the head.[11 12]

Helmets can prevent skull fractures and catastrophic head injuries, although the ability to prevent concussion is less clear.[13] There is the potential for a helmet to change the burden of injury by converting a potentially serious brain injury incident into a concussion incident. Several previous epidemiological studies among recreational skiers and snowboarders, including two case –control studies and a long-term (1995/1996–2011/2012) prospective epidemiological study, have documented that the use of helmets significantly reduces the risk of head injury and does not increase the risk of neck injury.[14–18]

In all FIS WC events, helmets are mandatory during official training, course inspection and competitions.[19] Prior to the 2013–2014 WC season, FIS enforced a new helmet testing rule for alpine downhill, super-G and giant slalom and for freestyle ski cross.[19] Under the new safety rule, helmets must be certified to both American Society for Testing and Materials (ASTM) F2040 and European Standard(EN) 1077:2007 (class A) standards. In addition, the helmets are required to pass a 6.8 m/s impact energy attenuation drop test using the EN 1077 method. The additional test corresponds to a drop height of 2.4 m.[19] However, this new, stricter rule has not been enforced by FIS for snowboarding or for the other freestyle disciplines.[19]

Since the start of the FIS Injury Surveillance System in 2006/2007, it has been mandatory for snowboard and freestyle skiing helmets to comply with either EN 1077 (Class B) or ASTM F2040, as minimum standards.[19] However, helmets fulfilling higher safety standards such as EN 1077 (Class A) or Snell Memorial Foundation (Snell) RS-98 could also be used.[19] The EN 1077 test standard has a pass/fail criterion for peak linear maximum headform acceleration of 250 g (g_{max} <250 g) in flat anvil impacts at 5.4 m/s.[20] In comparison, the pass/fail criteria in both the ASTM F2040 and Snell RS-98 standards is 300 g peak linear headform acceleration (g_{max} <300 g) in 6.2 m/s and 6.3 m/s, respectively, flat anvil impacts.[21 22]

Previous research has documented the need to target future injury reduction strategies in snowsport helmet design towards both severe head injuries and concussions.[23] The new helmet rule represents an attempt to reduce the rate of severe head injuries. Helmets are predominantly designed for impacts on rigid surfaces (such as roads or pavements) and not for impacts on more compliant surfaces such as snow or ice.[24] Impact surfaces in helmet testing standards are mainly rigid steel anvils. These test surfaces are not designed to simulate real-world conditions but rather to represent severe impact surfaces that allow helmet performance to be evaluated and facilitate test repeatability and reproducibility.[24] Therefore, future helmets should be developed and evaluated also with regard to realistic impact conditions, such as impacts onto snow and ice for skiing and snowboarding helmets.[23]

Recent studies based on numerical modelling or anthropomorphic test devices have described snowboarding normal-to-slope head impact velocities of 7.8±1.7 m/s and 8.11 m/s.[25 26] These studies indicate that head impact velocities might be slightly higher than the new strictest helmet testing rule.[25 26] However, how these studies, and the increased helmet testing speed, relate to head impact velocities in real head injury situations on snow is unclear.

The current direction in helmet development and testing is to consider the capacity of helmets to manage the head's angular kinematics (acceleration and/or velocity).[23 27 28] At present, angular kinematic management is not considered in any national or sports-specific standard. Therefore, it is of interest to describe angular kinematics during helmeted real-world impacts in as much detail as possible, with the data obtained from this video analysis.

Our study aims were: (1) to describe the injury mechanisms in a selection of head impact injury cases among WC snowboard and freestyle athletes, (2) to describe the gross head impact biomechanics and (3) to compare the head impact characteristics with relevant helmet standards.

METHODS

Medical information

Medical information about the selected cases was obtained through the FIS Injury Surveillance System (FIS ISS) based on data from 8 WC seasons (2006–2014).[2–4 29] A total of 75 WC competition head/face injuries (snowboard n=40, freestyle n=35) were registered in the FIS ISS database during eight seasons (figure 1). Medical information about one case was obtained through the IOC injury and illness surveillance system for multisport events, used during the 2014 Winter Olympic Games in Sochi, Russia (figure 1).[30]

Video collection and processing

All videos from the FIS WC competitions were collected retrospectively at the end of each of the eight seasons from the FIS WC television producer (Infront Media). As only competition runs are filmed by the television producer, no videos of warm-up or training runs were acquired. One additional video (case 4) was obtained from the IOC Olympic Multimedia Library. Of the 76 head injuries recorded, we obtained 16 videos with a clear view of the incident (figure 1). In other cases, the camera view of the incident was obscured by snow spray, athletes, the terrain (bumps and jumps) and camera zooming or panning, athletes crashing out of camera view or other circumstances (figure 1).

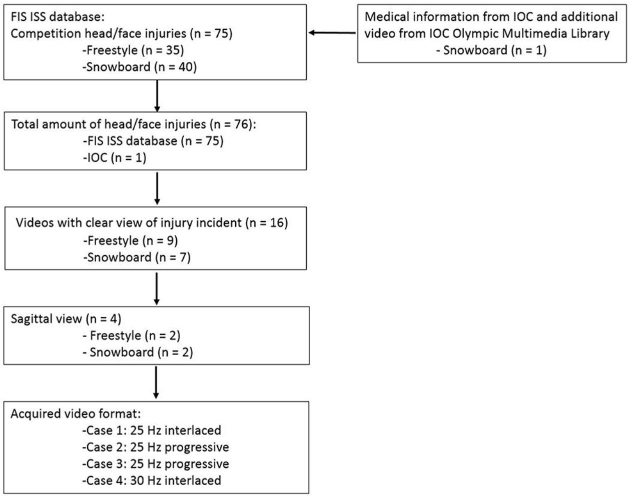

Figure 1 Flow chart of the video acquisition process. FIS ISS, International Ski Federation Injury Surveillance System; IOC, International Olympic Committee.

The main criterion for including the videos was a primarily sagittal view of the athlete during the incident. Of the 16 (FIS n=15, IOC n=1) available videos of competition injuries, only four met this criterion. Two of the videos obtained had a progressive scan with a frame rate of 25 Hz, while two of the videos were obtained in an interlaced format, making it possible to double the effective frame rate to 50 Hz and 60 Hz (figure 1). We deinterlaced and edited the videos using Adobe Premiere Pro CS6 (Adobe Systems, San Jose, California, USA). We edited the videos to obtain square pixels (1:1 pixel aspect ratio), and the videos had a display resolution of 1024×576 pixels (case 1), 788×576 pixels (cases 2 and 3) and 1920×1080 pixels (case 4). We obtained the ski or snowboard dimensions from the athlete or their ski/snowboard supplier. The ski/snowboard lengths ranged between 150 cm and 191 cm. Based on this information, we could calculate the pixel size to range from 0.8 cm to 1.3 cm. The pixel size was calculated at the ski/snowboard measurement frame.

Linear movement analysis

A commercial software programme for video-based movement analysis (SkillSpector, V.1.3.2, Odense, Denmark) was used to digitise a fixed point on the helmet, as well as two reference points in the surroundings. The local calibration frame was positioned at the frame of helmet impact, using the length of the ski/snowboard for scaling. The measurement of the ski/snowboard was performed at the closest possible frame to the frame of impact where we could see the ski/snowboard perpendicularly and in full length. As we could not see the ski/snowboard perpendicularly and in full length during the helmet impact frame in any of the cases, the measurement frame is therefore not the same as the calibration frame. The mean time from the measurement frame to the calibration frame for all four cases was 0.3 s. The calibration frame was positioned in relation to the slope of the surface during the helmet impact. We could only assess the slope of the surface in the sagittal plane. We assumed that the vertical direction of the video footage was aligned with the true vertical axis.

We used a smoothing spline algorithm with a 15 Hz cut-off to calculate head velocity.[31] To determine the change in linear

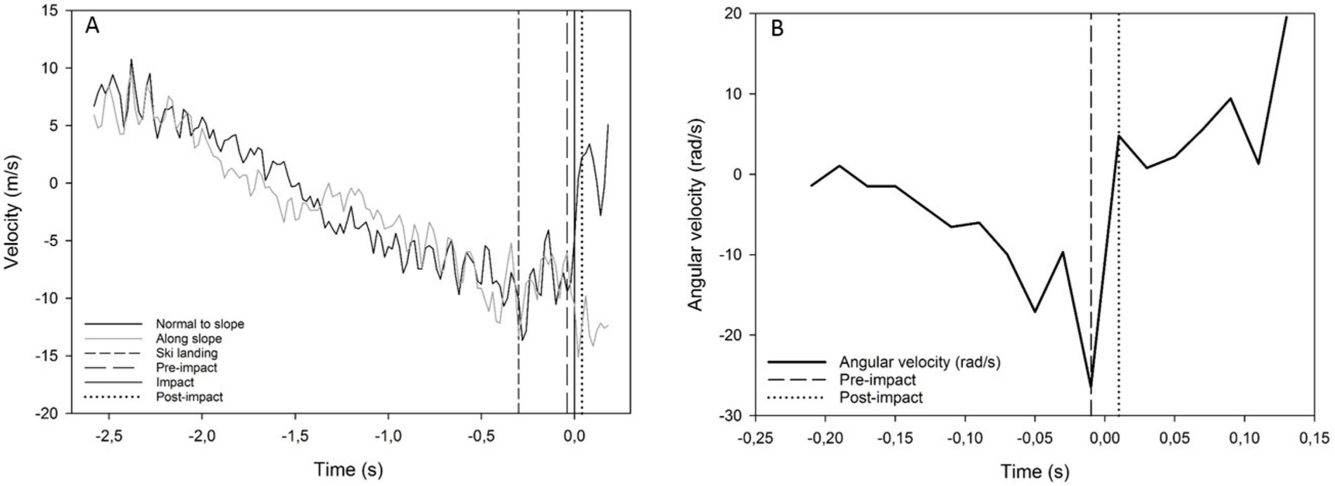

Figure 2. (A) Estimated filtered velocity of the digitised helmet point of case 1, including the ski landing frame (−0.30 s) and preimpact (−0.04 s) and postimpact (0.04 s) frames, used as variables to describe the velocity change in the normal-to-slope and along-slope directions. (B) Estimated helmet angular velocity in the sagittal plane (unfiltered) of case 1, including the preimpact (−0.01 s) and postimpact (0.01 s) frames. The impact frame (0.0 s) is midway between the preimpact and postimpact frames.

velocity in the normal-to-slope and along-slope directions, we extracted variables from preimpact and postimpact frames, immediately before and after (maximum two frames (40 ms)) the head impact (figure 2A). The lowest downwards velocity immediately preimpact was reported, in addition to the highest upwards velocity immediately postimpact (figure 2A).

Error assessment

The same person performed three digitising trials of the helmet for each case and we report the mean±SD of the three trials. As a measure of the intrarater digitising error, we calculated the root mean square error (cm) of the helmet position (normal and along slope) between the three digitising trials for all four cases and report the mean. Furthermore, we performed three digitising trials of the pelvis during the flight phases and fitted a linear regression line for the mean velocity of the pelvis for the flight phases of cases 1, 2 and 4 (case 3 did not have a flight phase). For the digitisation of the pelvis, it was possible to perform the ski/board measurement and the calibration in the same frame. The calibration frame was aligned with the video image.

We reported the root mean square error (m/s) from the regression line of the flight phases in both the vertical and horizontal directions (figure 3); the estimated vertical and horizontal acceleration of the estimated centre of mass (represented by the pelvis) due to gravity during the flight phases of cases 1, 2 and 4 (figure 3); and the root mean square error of the three trials of the angular measurement of the helmet.

Head impact angle

The head impact angle is defined as the angle of the head velocity vector prior to impact relative to the slope at the frame of impact. The head impact angle is therefore not the orientation of the helmet to the snow.

Angular movement analysis

We measured the sagittal plane angular velocity of the helmet frame by frame, from at least 10 frames preimpact to at least five frames postimpact, using an angle measurement software (MB Ruler V.5.3, Markus Bader—MB Software Solutions). We aligned the MB Ruler visually with an estimated alignment close to the Frankfurt plane, represented by the goggle band, on a frame-by-frame basis. We did three trials for each case and we report the mean angular velocity. Angular velocity was estimated as the change in angle between two frames divided by the time interval. No filtering was done. To estimate the change in angular velocity, we used the lowest negative point of the preimpact angular velocity and the peak of the postimpact angular velocity (maximally two frames (40 ms or less) before and after the impact) (figure 2B).

Injury severity

The FIS ISS classifies injury severity according to the duration of absence from training and competition as: slight (no absence), minimal (1–3 days), mild (4–7 days), moderate (8–28 days) and severe (>28 days).[29] This classification of injury severity is an operational injury definition within the FIS ISS (where all

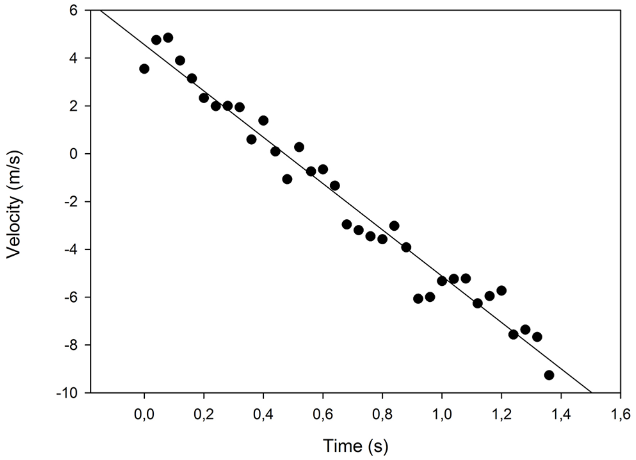

Figure 3 Vertical velocity of the flight phase of case 2, fitted with a linear regression line to estimate vertical acceleration due to gravity and the root mean square error (m/s).

Table 1 Description of the four head impact injury cases

	Case 1	Case 2	Case 3	Case 4
Sex	Male	Male	Female	Female
Age at time of injury	21	18	21	24
Season of injury	2012/2013	2007/2008	2010/2011	2013/2014
Diagnosis	Concussion	Concussion	Concussion	Concussion
Severity (absence)	4–7 days	4–7 days	8–28 days	0
Discipline	Ski halfpipe	Ski cross	Snowboard cross	Snowboard slopestyle
Competition	World Cup competition	World Cup competition	World Cup competition	Olympic Winter Games

injuries and not only head/face injuries are registered) and therefore not a head injury-specific definition of severity.

RESULTS

The four head impact injury cases analysed were from four different freestyle and snowboard disciplines and all resulted in concussion (table 1; figures 4–7). In all four cases, the impact location was to the rear of the helmet. In the two skiing situations, the athlete landed rear-weighted and fell backwards while the skis were pointing in the direction of movement. In contrast, the two snowboard injuries resulted from catching the back edge when the athlete had her back to the direction of movement.

Linear velocity

The normal-to-slope preimpact velocity ranged from 7.0±0.2 m/s to 10.5±0.5 m/s and the normal-to-slope velocity change ranged from 8.4±0.6 m/s to 11.7±0.7 m/s (table 2). For all cases, there was a greater change in velocity from preimpact to postimpact in the normal-to-slope direction compared with the along-slope direction (table 2, figure 2A). For cases 2, 3 and 4, the contribution of the along-slope component was minor. However, for case 1, the along-slope component was substantial (table 2).

The impact angles of the head velocity vector relative to the slope at the frame of impact were 57°, 25°, 54° and 45° for cases 1 to 4, respectively.

Angular velocity

All cases displayed peak head angular velocity immediately prior to impact. The peak ranged from 42.7±0.5 to 22.9±1.4 rad/s (figure 2B; table 2). Within 40 ms of impact, there was a rebound motion of the head in all cases. The maximum rebound angular velocity ranged from 2.1±1.6 to 8.1±0.5 rad/s. The total change in angular velocity ranged from 25.0±2.9 to 49.1±0.3 rad/s (table 2).

Estimation of error

The root mean square error of the vertical velocity of the pelvis during the flight phases was 1.55 m/s, 0.71 m/s and 0.47 m/s from the regression line for cases 1, 2 and 4, respectively. Standard acceleration due to gravity is 9.81 m/s^2, and is therefore the target value for our vertical acceleration estimates. The acceleration due to gravity during the flight phases was estimated to be 10.3 m/s^2, 9.7 m/s^2 and 10.7 m/s^2 for cases 1, 2 and 4. Our target measure for the horizontal component of the gravitational acceleration is 0 m/s^2. The horizontal acceleration was 0.7 m/s^2, 2.7 m/s^2 and 1.3 m/s^2, and the root mean square error in the horizontal direction was 1.7 m/s, 1.4 m/s and 0.8 m/s for cases 1, 2 and 4, respectively.

The mean root mean square error of the three digitising trials of the helmet of cases 1 to 4 in the normal-to-slope direction was 1.9 cm and 1.7 cm in the along-slope direction .

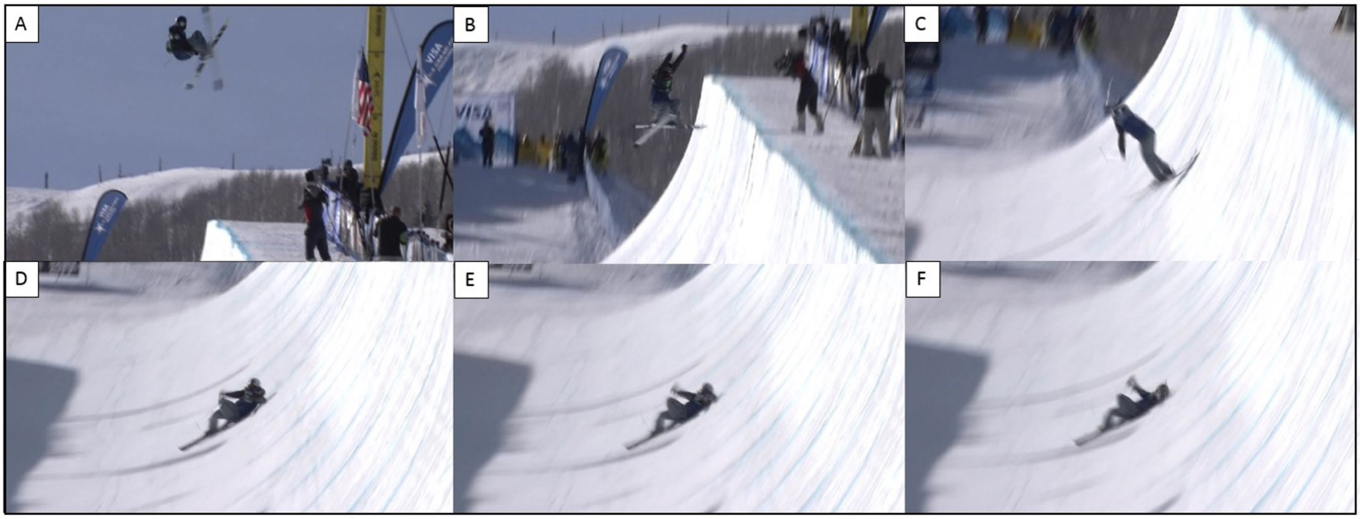

Figure 4 Case 1 (50 Hz). Key crash events: (A) the highest point of the athlete's trajectory, (B) descending towards the vertical part of halfpipe wall, (C) ski landing frame (first impact of ski tails), (D) buttocks and lower back contact with snow, (E) upper back contact with snow, (F) head impact frame.

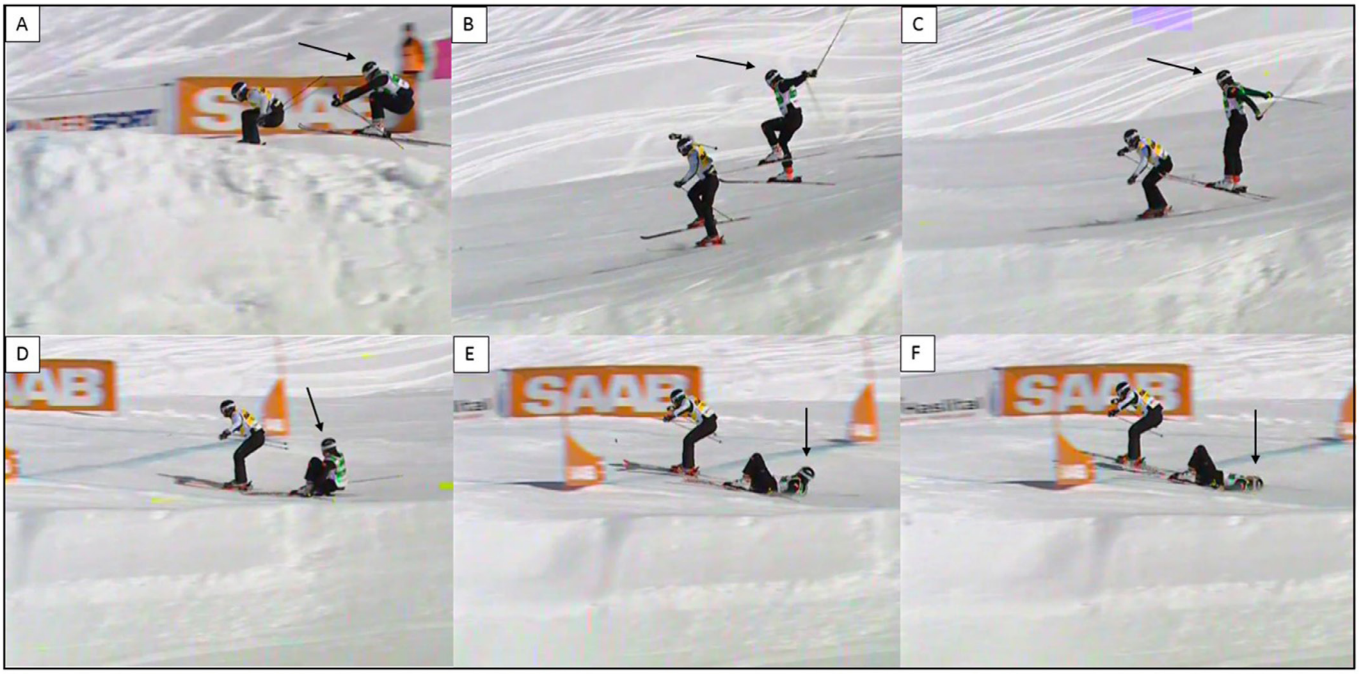

Figure 5 Case 2 (25 Hz). Key crash events (the black arrows point to the injured athlete): (A) the athlete is in flight following a jump, (B) the athlete loses balance during flight, creating an out of balance movement backwards, (C) ski landing frame (first contact of tails of skis), (D) buttock contact with snow. Trunk and hip in flexed positions, (E) upper back contact with snow. Hip and trunk extend. The athlete's shoulders extend, (F) head impact frame.

Figure 6 Case 3 (25 Hz). Key crash events: (A) the athlete is approaching a banked turn, (B) the athlete loses control of her board and her back edge catches, (C) the body rotates about the board, (D) the athlete continues to rotate and translate along the ground. The hip and trunk are maximally flexed, (E) the athlete lands on her buttocks and continues to rotate posteriorly while the hip and upper body extends. The athlete extends her shoulders, (F) head impact frame.

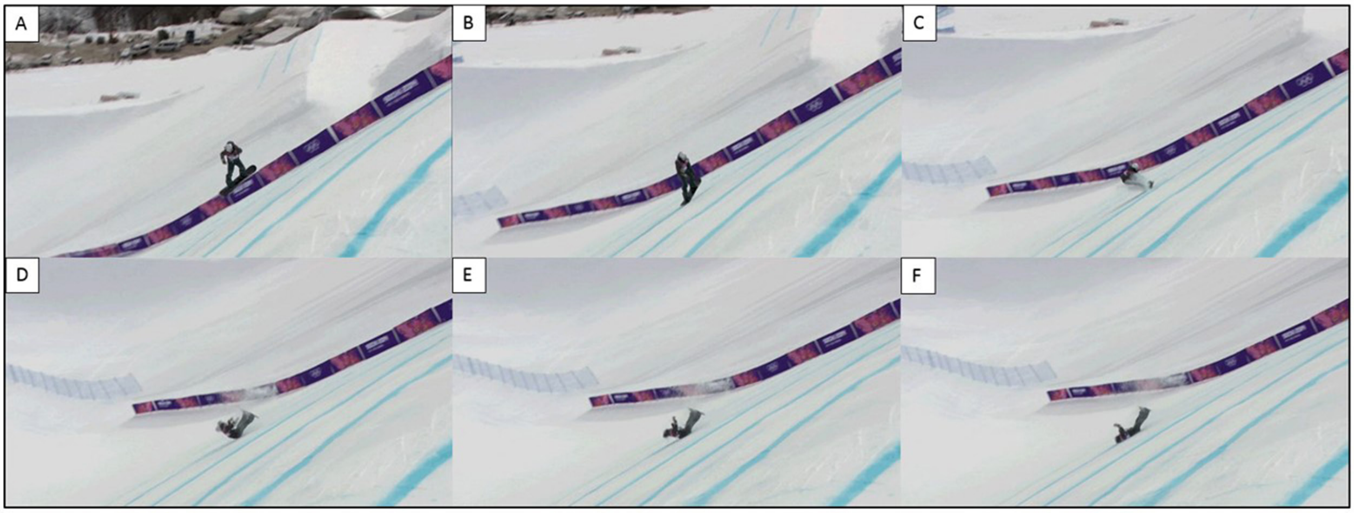

Figure 7 Case 4 (60 Hz). Key crash events: (A) the athlete is airborne, approaching her landing, (B) board landing frame (first contact of board to snow), (C) the back edge catches.The body rotates about the board. The hip and trunk are maximally flexed, (D) the athlete continues to rotate and translate along the ground and lands onto her buttocks, (E) extension of the hip and trunk, (F) head impact frame.

The mean root mean square error of the three trials of the angular measurement of the helmet was 3°.

DISCUSSION

This is the first study to report head impact velocities of real concussive events in FIS WC snowboarding and freestyle skiing. In all four cases, the estimated normal-to-slope preimpact velocity was greater than the prevailing minimum requirements at the time of the incidents of 5.4 m/s (EN 1077), 6.2 m/s (ASTM F2040) and the current FIS helmet rule of EN 1077 plus ASTM F2040 plus 6.8 m/s impact test for alpine giant slalom, super-G and downhill and freestyle ski cross. The change in head velocity during impact in the normal-to-slope direction ranged from 8.4±0.6 m/s to 11.7±0.7 m/s. For three of the four cases, the along-slope velocity change was minor, while in one case, the along-slope component was substantial. However, the significance of this along-slope velocity change in relation to helmet testing standards is unclear. The sagittal plane angular velocity estimates indicated a rapid backwards head rotation with a large change in angular velocity (25.0±2.9 rad/s to 49.1±0.3 rad/s) during impact.

Gross injury mechanisms

Our four injury cases represent common head impact scenarios in snowboarding and freestyle skiing. The gross injury mechanism of our two snowboarding cases (cases 3 and 4) was a ‘back-edge catch’ , which is previously described as a common head gross injury mechanism in snowboarders.[32] Previous studies have described that the most frequent causes of snowboarding head injuries are simple falls on slopes in beginners and falls during jumping in experts, while the most common injury mechanism is falling backwards, leading to an occipital impact.[33–35]

The gross injury mechanisms of our two freestyle skiing cases (cases 1 and 2) are similar to ‘slapback’ mechanisms in aerials skiers. In aerials skiers, slapback head injuries typically occur when a skier over-rotates in the air during an inverted

Table 2 Estimated linear velocity of the digitised helmet points including the change in head velocity, and estimated angular velocity of cases 1 to 4 (±SD for the three trials). Negative velocity refers to downward movement (towards the slope) in the normal-to-slope direction, while positive velocity refers to a rebound (upwards) movement. Negative angular velocity refers to a head rotation towards extension, while positive angular velocity refers to a head rotation towards flexion. A negative velocity change in the along-slope direction indicates a decrease in velocity from preimpact to postimpact, while a positive along-slope velocity change indicates an increase

	Case number	Frame rate analysed (Hz)	Preimpact velocity (±SD)	Postimpact velocity (±SD)	Change in velocity (±SD)
Normal-to-slope velocity (m/s)	1	50	−9.4 (0.3)	2.3 (0.7)	11.7 (0.7)
	2	25	−7.0 (0.2)	1.4 (0.5)	8.4 (0.6)
	3	25	−8.9 (0.1)	1.1 (0.2)	10.0 (0.3)
	4	60	−10.5 (0.5)	0.2 (0.1)	10.7 (0.6)
Along-slope velocity (m/s)	1	50	6.1 (0.1)	12.3 (0.6)	+6.2 (0.7)
	2	25	15.1 (0.1)	17.4 (0.1)	+2.3 (0.1)
	3	25	6.5 (0.2)	5.6 (0.1)	−0.9 (0.2)
	4	60	10.6 (0.5)	8.3 (0.6)	−2.3 (0.9)
Angular velocity (rad/s)	1	50	−26.4 (1.3)	4.8 (2.0)	31.2 (3.2)
	2	25	−22.9 (1.4)	2.1 (1.6)	25.0 (2.9)
	3	25	−42.7 (0.5)	6.4 (0.4)	49.1 (0.3)
	4	60	−32.2 (3.2)	8.1 (0.5)	40.3 (3.1)

jump, causing further backward rotation after the ski tails have contacted the snow, with the back and head ultimately impacting the landing surface.[36] Our freestyle cases were not aerials skiers, and there is an important differences in the landing dynamics of aerials skiers compared with our two cases: aerials skiers land on a steep landing zone (37°) with chopped snow, as opposed to our freestyle cases who landed on hard snow in flatter areas.[37] Both freestyle aerials and half pipe athletes (case 1) perform inverted jumps, while in ski cross (case 2) this is not the case. In addition, in freestyle aerials, due to the steepness of the landing slope, the skiers do not usually impact the snow with their buttocks. Nevertheless, despite these differences, the slapback head injury mechanism seems to be similar in our two cases compared with aerials skiers.

Considering the gross injury mechanisms, our cases of snowboarding back edge catches demonstrated different crash dynamics than previous studies using laboratory reconstructions with Hybrid III anthropomorphic test devices.[25 38] These studies demonstrated anthropomorphic test devices being flipped up in the air after the edge catch, with the spine and hips in full extension, before landing on the head, without the buttocks or back contacting the snow.[25 38] In contrast, the observed gross injury mechanism in our study involved the following sequence: edge catch, buttock contact with snow, back contact and finally head contact with snow (figures 6 and 7). Richards *et al*[25] reported that the mean normal-to-slope head impact velocity was 8.11 m/s, corresponding to a helmet drop height of 3.4 m, and the resultant velocity was 10.6 m/s, which despite the differences in study approach and crash mechanism is very similar to our results.

One previous study can help shed light on the forces involved in slapback mechanisms. Meacham *et al*[36] instrumented the helmets of aerials skiers with triaxial accelerometers and reported maximum impact accelerations during real-life slapbacks of 27–92 g with a maximum duration of impacts of 12–96 μs.[36] Severity indices were considered low in terms of life-threatening injury levels. However, as Meacham *et al*[36] did not report velocity changes, a direct comparison with our data is not possible.[36]

Head impact velocities in alpine sports

Yamazaki *et al*[39] described the head impact velocity of one real-life case of a downhill alpine skiing severe TBI. This was a high-speed crash landing after a large jump, where the athlete landed partly sideways. Yamazaki *et al*[39] reported a velocity change of 11 m/s in the normal and along-slope directions, and a frontal plane angular velocity change of 100 rad/s.[39] The angular velocity change was substantially greater than in our cases. The difference in skiing speed and the different circumstances surrounding the crashes, such as the landing variables (snow properties, size of the jump, drop height and steepness of the landing/impact slope) should be considered when comparing the results.

Although a description of head impact velocities is essential with respect to informing helmet testing standards, snow properties will influence the peak head accelerations during a crash. Although FIS WC-prepared snow is generally hard or icy, it is essential for future studies to investigate snow properties such as the liquid–water content, density and texture when reporting head impact magnitudes. In addition, the impact angle of the slope must be considered.

Scher *et al*[38] reported that during back edge catches, the peak linear accelerations on soft snow were 83 g with and 74 g without a helmet, and on hard/icy snow 162 g with and 391 g without a helmet. From qualitative video analysis, it is difficult to assess snow properties. Therefore, future laboratory or field-based studies should examine snow properties quantitatively and in detail.

Head impact velocities in other sports

We do not know the head accelerations in our four cases. Therefore it is difficult to compare our findings to acceleration measures from head impacts in other sports. Still, the head impact velocity changes we found in our four cases are comparable to velocity changes in American football (range 7.2 m/s to 9.3 m/s), where also corresponding peak linear accelerations (range 64 g to 112 g) and angular accelerations (range 4253–8022 rad/s^2) have been reported.[40–42] Viano *et al*[40] reported an angular velocity change of 34.8 ± 15.2 rad/s, which is similar to our range.[40] The velocity changes we reported are also similar to concussive head impacts in unhelmeted Australian football and rugby players, where the linear peak velocity change ranged from 3.2 to 9.3 m/s.[43]

Relevance for helmet testing standards

Of the four cases we have analysed, the new helmet rule (both EN 1077 and ASTM 2040 and additional EN 1077 test of 6.8 m/s) only applies to one case (case 2), who is a ski cross athlete. However, the freestyle ski cross case we have analysed (case 2) is from 2008 (ie, the injury occurred in 2008), which is before the new rule was implemented. None of our four cases were required to have helmets complying with the new FIS helmet rule at the time of injury. Case 4 was injured after the implementation of the new rule (during the 2013/2014 season) but belongs to a discipline where the new helmet rule has not been enforced (snowboard slopestyle).

Under current rules, only case 2 (freestyle ski cross) belongs to a discipline where the new standard has been enforced. The other cases can still comply with the original test standards (EN 1077, impact velocity 5.4 m/s or ASTM F2040, impact velocity 6.2 m/s).

The preimpact velocity, which relates most directly to the height specified in helmet drop tests, was for all of our cases higher than the prevailing requirements at the time of the incidents (5.4 m/s (EN 1077) or 6.2 m/s (ASTM F2040)) and the current FIS rule of EN 1077 plus ASTM F2040 plus 6.8 m/s impact test. Nonetheless in three of the four cases studied, which only comprise 5% (4/76) of the sample of head injury cases, the athlete's absence due to injury was less than 7 days. This suggests that the helmets worn provided substantial protection to the head against moderate to severe TBI and might exceed the homologation requirements. Homologation requirements are minimum performance requirements; for example, McIntosh and Patton[44] observed in two AS/NZS 2063-compliant bicycle helmets that the peak headform acceleration at a drop height of 2.5 m remained under the 250 g pass level for the 1.5 m requirement mandated in AS/NZS 2063.[44] The helmet models, condition and impact damage in three of our four cases is unknown. It was well documented by the media during the 2014 Olympic Winter Games in Sochi that the helmet in case 4 broke during the crash. However, we do not know the precrash condition of the helmet.

Ideally, this study would be complemented by inspection of the helmets worn and testing of exemplar helmets. The results do not provide a strong case for changing the helmet impact speeds in FIS-mandated standards for these sports and are limited by the sample size, helmet models and our understanding of the differences between real-world impacts on snow and laboratory impacts.

An impact anvil is typically rigid, which will produce a higher head acceleration compared with a real-world impact against a compliant surface such as snow/ice. Headforms used in laboratory tests are also rigid and will produce a higher head acceleration compared with a human head or equivalent headform.[39] For those reasons, when considering equivalence between real-world impacts and laboratory tests, laboratory helmet testing velocities on rigid anvils are often lower than what is observed in real-world impacts.[39]

Angular kinematics

Our findings indicate that there is a considerable angular velocity change of the head in each crash. It is important to consider the angular kinematics of the head in the causation of brain injuries.[45 46] In comparison with helmet drop tests, in which preimpact angular motion is minimal and angular motion during the impact is constrained by the test system, our results identified that, during the fall, the head had developed angular velocity preimpact and there was a greater change in angular velocity during impact. Both linear and angular velocity results demonstrated that there was a rebound phase, which might not be anticipated in an impact with soft snow. This change in head angular velocity would be reflected in head angular acceleration. The helmet and snow/ice impact interface may both contribute to rebound. Further research is required on the snow/ice impact interface. Measurements of rebound on 150 motorcycle helmets in drop tests show that the coefficient of restitution (CR) varies by helmet model and drop height.[47] For example, the average CR was 0.35 in 0.8 m drop tests compared with 0.27 in 2.5 m drop tests, where the mandated drop height in United Nations Economic Commission for Europe (UNECE) 22 (motorcycle helmets) is 2.5 m.[47] These results suggest that the selection of the foam liner properties is important and may be tuned to specific impact management requirements in standards. This issue might be addressed in a standard by (1) including a performance criteria for coefficient of restitution or (2) including an oblique impact test[27 28] to assess the ability of the helmet to manage the head's angular kinematics. The impact angles of the helmet velocity vector relative to the slope at the frame of impact were between 25° and 57°. However, in our cases, we do not have information about the snow properties, muscle activation (such as neck muscle contraction) or force transfer from the body or neck to the head at the impact, which makes the consequence of the impact angles difficult to consider. Importantly, we also do not have information about angular velocity changes in other planes of movement. Yamazaki *et al*[39] described a frontal plane angular velocity change of 100 rad/s after a high-speed sideways fall. In other words, angular velocity changes can be considerably greater than we described, and may occur in all three planes.

What are the findings?

- This is the first study to describe the gross head impact biomechanics, and to report head impact velocities of four real concussive events in International Ski Federation World Cup snowboarding and freestyle skiing.
- In all four cases, the estimated normal-to-slope preimpact velocity was higher than the prevailing helmet standards (5.4 m/s and 6.2 m/s) at the time of injury and higher than the current strictest helmet testing rule of 6.8 m/s.
- The helmets offered a high level of protection to the head.
- The head may undergo a considerable angular velocity change during the head impact which may contribute to brain injury and may be influenced by the snow/ice interface and the helmet foam liner characteristics.

How might it impact on clinical practice in the future?

- This study provides important information about real-life head impact velocities and gross head impact biomechanics in snowboarding and freestyle skiing.
- Information about real-life head impact velocities and accurate descriptions of the mechanisms of head injuries are important considerations if helmet testing is to be developed and evaluated with regard to realistic impact conditions.
- Future laboratory or field-based studies should examine snow properties quantitatively and perform helmet impact tests on real-life snow and ice.

LIMITATIONS

The study sample was derived systematically from a prospective collection of videos from a defined athlete population. This process produced only a limited number of cases with a sagittal view of the crash on video. Therefore, we cannot be certain that the injury videos are representative of head injury situations in this WC cohort. Based on previous literature from the recreational level, there is a compelling argument that the injury mechanisms analysed in this study are representative.[32 35]

Comparing our four concussive cases with similar control cases would have been helpful in identifying head impact velocities in concussions compared with in non-concussive events (controls). However, we were not able to find suitable control videos.

TV footage will typically become blurry when there are large velocity changes. Coupled with limited frame rate (25–60 Hz), this makes it challenging to estimate impact velocities accurately. However, our error assessments showed that the measurements were reasonably accurate. We attempted to optimise the accuracy by performing three trials for the linear velocity and angular velocity measures, and reporting the mean. The mean root mean square error of the digitised head position was under 2 cm, indicating that the intrarater digitising was consistent between trials. However, it remains unclear how digitisation by different persons would have influenced the outcome measures.

Also the video resolution, the athlete's pixel size in the video image as well as the visibility of landmarks in the background may influence the estimation of displacement time data from the videos. The main limitations in our velocity analyses, however, are not from the limited spatial resolution but from snow spray, camera blur and limited temporal resolution. Blur is mainly a problem in the few frames immediately after impact. Hence, it was not possible to accurately measure the kinematics during the short duration of the impact. Image quality until the last frame before impact allowed for accurate visualisation of helmet reference points and estimation of head velocity immediately before impact, as verified by the estimates of vertical acceleration during flight.

We also cannot be certain that the video footage is aligned with the true vertical axis. In response, we partly verified this by reporting the vertical acceleration and root mean square error during the flight phase. The root mean square error during the flight phase of three cases ranged between 0.47 and 1.55 m/s from the regression line, indicating a low error of our vertical velocity estimates in cases 2 and 4, while the error was higher in case 1. However, although we have error estimates for the vertical velocity, we do not know how this error translates to the normal-to-slope and along-slope velocity measures.

The estimated vertical acceleration during the flight phases of cases 1, 2 and 4 was close to the gravitational acceleration constant of 9.8 m/s^2, which indicates that the accuracy of our vertical velocity estimates was reasonable, while our horizontal error was greater. The relatively accurate results relating to the vertical acceleration measurements most likely arose because of the restrictive case inclusion and exclusion criteria. However, we do not know what is likely the cause of the discrepancy between the estimated acceleration due to gravity and the target value of 9.8 m/s^2. Possibly, this could be due to discrepancies relating to the vertical axis of the camera, digitisation error or calibration length error.

We chose not to filter the angular velocity signal, considering that this would give the most realistic estimate of the actual angular velocity. The reason is that the change in head rotation could be as high as 40° between two frames. A filter would underestimate the measured angular velocity change between two frames considerably. Therefore, some caution and interpretation are required if these angular velocity change estimates were to be compared with angular velocity measured in controlled experiments using defined signal conditioning methods.

CONCLUSION

In all four cases, the estimated normal-to-slope preimpact velocity was higher with regard to the prevailing helmet standards at the time of injury and higher than the current strictest helmet rule of 6.8 m/s. Considering this, helmets offered a high level of protection to the head: there were no skull fractures and absence due to injury was less than 7 days in three cases. The study identified a method for studying gross injury mechanisms and head kinematics that needs to be reproduced on a larger sample. The study identified that the head may undergo a considerable angular velocity change during the head impact which may contribute to brain injury and that may be influenced by the snow/ice interface and the helmet foam liner characteristics.

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Competing interests None declared.

Patient consent Detail has been removed from this case description/these case descriptions to ensure anonymity. The editors and reviewers have seen the detailed information available and are satisfied that the information backs up the case the authors are making.

Ethics approval The project has been reviewed by the Regional Committee for Medical Research Ethics, South Eastern Norway Regional Health Authority, Norway, and approved by the Social Science Data Services.

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REFERENCES

1 SnowSports Industries America. USA Snowsports Organizations Factsheet 2016. http://www.snowsports.org/research-surveys/snow-sports-fact-sheet/ (accessed 15 Nov 2016).
2 Major DH, Steenstrup SE, Bere T, *et al*. Injury rate and injury pattern among elite World Cup snowboarders: a 6-year cohort study. *Br J Sports Med* 2014;48:18–22.
3 Flørenes TW, Heir S, Nordsletten L, *et al*. Injuries among World Cup freestyle skiers. *Br J Sports Med* 2010;44:803–8.
4 Flørenes TW, Nordsletten L, Heir S, *et al*. Injuries among World Cup ski and snowboard athletes. *Scand J Med Sci Sports* 2012;22:58–66.
5 Hagel BE, Goulet C, Platt RW, *et al*. Injuries among skiers and snowboarders in Quebec. *Epidemiology* 2004;15:279–86.
6 Kim S, Endres NK, Johnson RJ, *et al*. Snowboarding injuries: trends over time and comparisons with alpine skiing injuries. *Am J Sports Med* 2012;40:770–6.
7 Steenstrup SE, Bere T, Bahr R. Head injuries among FIS World Cup alpine and freestyle skiers and snowboarders: a 7-year cohort study. *Br J Sports Med* 2014;48:41–5.
8 Ackery A, Hagel BE, Provvidenza C, *et al*. An international review of head and spinal cord injuries in alpine skiing and snowboarding. *Inj Prev* 2007;13:368–75.
9 Russell K, Meeuwisse WH, Nettel-Aguirre A, *et al*. Feature-specific terrain park-injury rates and risk factors in snowboarders: a case-control study. *Br J Sports Med* 2014;48:23–8.
10 Carús L, Escorihuela M. Feature-specific ski injuries in snow parks. *Accid Anal Prev* 2016;95:86–90.
11 Russell K, Meeuwisse W, Nettel-Aguirre A, *et al*. Characteristics of injuries sustained by snowboarders in a terrain park. *Clin J Sport Med* 2013;23:172–7.
12 Carús L, Escorihuela M. Epidemiology of feature-specific injuries sustained by skiers in a snow park. *Wilderness Environ Med* 2016;27:415–20.
13 Bonfield CM, Shin SS, Kanter AS. Helmets, head injury and concussion in sport. *Phys Sportsmed* 2015;43:236–46.
14 Sulheim S, Holme I, Ekeland A, *et al*. Helmet use and risk of head injuries in alpine skiers and snowboarders. *JAMA* 2006;295:919.
15 Russell K, Christie J, Hagel BE, *et al*. The effect of helmets on the risk of head and neck injuries among skiers and snowboarders: a meta-analysis. *CMAJ* 2010;182:333–40.
16 Hagel BE, Russell K, Goulet C, *et al*. Helmet use and risk of neck injury in skiers and snowboarders. *Am J Epidemiol* 2010;171:1134–43.
17 Macnab AJ, Smith T, Gagnon FA, *et al*. Effect of helmet wear on the incidence of head/face and cervical spine injuries in young skiers and snowboarders. *Inj Prev* 2002;8:324–7.
18 Shealy JE, Johnson RJ, Ettlinger CF, *et al*. Role of helmets in mitigation of Head Injuries: epidemiologic study of Head Injuries to skiers. *Skiing Trauma and Safety* 2015;20(STP1582):22-36. 2015 20.STP1582.22.36.
19 FIS. FIS Specifications for competition equipment and commercial markings. http://www.fis-ski.com/mm/Document/documentlibrary/Marketing/04/30/53/Competitionequipment_1617_11072016_clean_English.pdf (accessed 29 Nov 2016).
20 . Standardisation CSN EN 1077: 2007 Helmets for alpine skiers and snowboarders 2007 https://www.en-standard.eu/csn-en-1077-helmets-for-alpine-skiers-and-snowboarders/?gclid=CNv2jaW229QCFQqBsgodEy8Dpg (accessed 26 June 2017).
21 ASTM International. *Standardisation ASTM F2040-11. Standard specification for helmets used for recreational snow sports*. West Conshohocken, PA: ASTM International, 2011.
22 SNELL Memorial Foundation. Standardisation SNELL Memorial Foundation RS-98. 1998 Standard for protective headgear. For use in recreational skiing and snowboarding. 1998.
23 McIntosh AS, Andersen TE, Bahr R, *et al*. Sports helmets now and in the Future. *Br J Sports Med* 2011;45:1258–65.
24 Connor TAMeng S, Zouzias D. CORDIS, . Head protection: a European training network for Advanced Designs in Safety. 2016 http://www.heads-itn.eu/pdfs/Helmets_Standard_Evaluation.pdf (accessed 26 June 2017).
25 Richards D, Carhart M, Scher I, *et al*. Head Kinematics During Experimental Snowboard Falls: Implications for Snow Helmet Standards. *J ASTM Int* 2008;5:101406.
26 Bailly N, Llari M, Donnadieu T, *et al*. Head impact in a snowboarding accident. *Scand J Med Sci Sports* 2016. [Epub ahead of print].
27 McIntosh AS, Patton DA. Boxing headguard performance in punch machine tests. *Br J Sports Med* 2015;49:1108–12.
28 McIntosh AS, Lai A, Schilter E. Bicycle helmets: head impact dynamics in helmeted and unhelmeted oblique impact tests. *Traffic Inj Prev* 2013;14:501–8.

29 Flørenes TW, Nordsletten L, Heir S, *et al*. Recording injuries among World Cup skiers and snowboarders: a methodological study. *Scand J Med Sci Sports* 2011;21:196–205.

30 Soligard T, Steffen K, Palmer-Green D, *et al*. Sports injuries and illnesses in the Sochi 2014 Olympic Winter Games. *Br J Sports Med* 2015;49:441–7.

31 Woltring HJ. A Fortran package for generalized, cross-validatory spline smoothing and differentiation. *Advances in Engineering Software* 1986;8:104–13.

32 Nakaguchi H, Tsutsumi K. Mechanisms of snowboarding-related severe head injury: shear strain induced by the opposite-edge phenomenon. *J Neurosurg* 2002;97:542–8.

33 Nakaguchi H, Fujimaki T, Ueki K, *et al*. Snowboard head injury: prospective study in Chino, Nagano, for two seasons from 1995 to 1997. *J Trauma* 1999;46:1066–9.

34 Fukuda O, Takaba M, Saito T, *et al*. Head injuries in snowboarders compared with head injuries in skiers. A prospective analysis of 1076 patients from 1994 to 1999 in Niigata, Japan. *Am J Sports Med* 2001;29:437–40.

35 Koyama S, Fukuda O, Hayashi N, *et al*. Differences in clinical characteristics of head injuries to snowboarders by skill level. *Am J Sports Med* 2011;39:2656–61.

36 Meacham MD, Greenwald RM, Macintyre JG, *et al*. Incidence and Severity of Head Impact during Freestyle Aerial Ski Jumping. *J Appl Biomech* 1999;15:27–35.

37 FIS. Aerials course specification. 2016 http://wiki.fisski.com/index.php/Aerial_Course_Specification (Accessed 18 Jul 2016).

38 Scher I, Richards D, Carhart M. Head Injury in Snowboarding: Evaluating the Protective Role of Helmets. *J ASTM Int* 2006;3:14203.

39 Yamazaki J, Gilgien M, Kleiven S, *et al*. Analysis of a severe head injury in World Cup alpine skiing. *Med Sci Sports Exerc* 2015;47:1113–8.

40 Viano DC, Casson IR, Pellman EJ. Concussion in professional football: biomechanics of the struck player--part 14. *Neurosurgery* 2007;61:313–28.

41 Pellman EJ, Viano DC, Tucker AM, *et al*. Concussion in professional football: reconstruction of game impacts and injuries. *Neurosurgery* 2003;53:799–814.

42 Beckwith JG, Greenwald RM, Chu JJ, *et al*. Head impact exposure sustained by football players on days of diagnosed concussion. *Med Sci Sports Exerc* 2013;45:737–46.

43 Fréchède B, McIntosh AS. Numerical reconstruction of real-life concussive football impacts. *Med Sci Sports Exerc* 2009;41:390–8.

44 McIntosh AS, Patton DA. Impact reconstruction from damage to pedal and motorcycle helmets. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology* 2012;226(3-4):274–81.

45 Gennarelli TA, Thibault LE, Adams JH, *et al*. Diffuse axonal injury and traumatic coma in the primate. *Ann Neurol* 1982;12:564–74.

46 Margulies SS, Thibault LE. A proposed tolerance criterion for diffuse axonal injury in man. *J Biomech* 1992;25:917–23.

47 Consumer Rating and Assessment of Safety Helmets (CRASH). What is CRASH? 2017 http://crash.org.au/what-is-crash.html (accessed 29 Mar 2017).

Head impact velocities in FIS World Cup snowboarders and freestyle skiers: Do real-life impacts exceed helmet testing standards?

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Notes